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Energy Harvesting: Power at Small Scale

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ABSTRACT

Energy harvesting is a new promising research area for portable electronics. Portable electronic devices have been typically limited by the finite lifetime and size of the internal batteries. This has been a constant conflict and tradeoff between battery size and device capabilities. For instance, cardiac pacemaker lifespan is mostly limited by battery size, which occupies at least half the available volume. Energy harvesting or energy scavenging is an alternative that extracts energy from the surroundings in order to operate. Energy harvesting is also an interesting approach when battery replacement is not possible or is too costly, such as deployment of sensors in remote areas for surveillance or environmental monitoring. One of the best known examples is the self-winding wristwatch that started from being completely mechanical and operated by the wearer's daily motion, to be nowadays a miniaturized electrical generator. Energy harvesting extracts energy from the surrounding by harnessing motion, vibrations, and temperature gradients among others. Kinetic energy generators extract energy by means of piezoelectric, electromagnetic, or electrostatic transduction techniques. Piezoelectricity is produced by materials with piezoelectric properties when subject to pressure, generating a voltage as a result. Electromagnetic transduction uses the relative motion of magnets and coils in order to induce a voltage. Electrostatic generators use the change of capacitance, by varying the separation between plates, to generate an electrical charge. Applications of the technology vary from consumer electronics, remote deployment of sensors to biomedical applications. This work presents the state-of-the-art on energy harvesting applications.

Keywords: energy harvesting, energy scavenging, biomedical applications, small scale

1. INTRODUCTION

Energy generation is a topic that when it comes into mind it usually means generation at large scale, such as petroleum-based power plants. Engineers have been able to harness energy from the environment to satisfy our needs. As a result, clean technologies are paving the road for energy generation from the wind, rivers, sea, and sun. When using our power hungry devices, it is necessary to think about the proximity of electrical outlets for our gadgets chargers or to carry spare batteries. This panorama is still not much different from several decades ago although our technological marvels still surprise us.

Technology has been evolving at a fast pace, electronic devices shrink in size while increasing computing power. The trend nowadays is to reduce power consumption as well. On the other hand, energy harvesting is another technology that has benefited from the decrease in power consumption. An example of this effect can be appreciated with the solar-powered calculator. Although there are devices that harness energy from the environment to operate, still they are a minority.

Most attention of electrical generators for portable applications is usually found in the form of solar chargers (passive) and hand-crank generators (active). Active generators are capable of producing a relatively large power output (2 W) at the expense of physical motion (Romero, 2012b). This is a good approach for emergency applications. The shake-driven flashlight is an example of this. Professional athletes can produce up to 600-800 W of power for short periods of time (Flipsen, 2005), but non-professional athletes can also produce continuously 14 W of electrical power through sustained hand cranking (Slob, 2000). Passive generation is an interesting approach since the generator is constantly charging without direct interaction. Physical motion or mechanical vibrations are usually the type of energy input for this kind of devices.

2. POWER LIMITS

Thermal energy generation is limited by the Carnot efficiency η_c that provides a limit for energy generation. Thus, higher temperature differences mean higher energy generation efficiency.

$$\eta_c = (T_{high}-T_{low})/T_{high}$$

Kinetic energy generation depends on the external motion or vibration. The available power (P_d) that a kinetic energy generator can produce is (Romero, 2010)

$$P_d = \frac{1}{2}\, m\, a^2/\omega\;\; Q$$

where m is the mass of the proof mass, a is the external acceleration, ω is the vibration frequency, and Q the quality factor of the generator.

Table 1 summarizes the energy level that some battery types are capable of providing, and Table 2 provides a guide of the power consumption that some medical devices consume. Table 3 offers a guide of what energy harvesters can supply (Mathuna et al., 2008).

Table 1: Energy Sources Summary

Energy Source		Energy Level (J)
Battery Type	Button Cell	~10^3
	AA Battery and/or Cellphone	~10^4
	Laptop	~10^5
	Lead Acid	~10^6

Table 2: Medical Equipment Power Requirements Summary

Medical Equipment	Power Requirement Order (W)
Exoskeleton - Prosthesis	~10^2 ~ 10
Retinal Stimulator - Neural Recorder	~10^{-1} ~ 10^{-2}
Cochlear Processor - Hearing Aid	~10^{-3} ~ 10^{-4}

Table 3: Energy Harvesters Summary

Condition	Power Density
Thermal (ΔT = 5K)	60 µW/cm^2
Solar (Indoor - Outdoor)	100 - 7500 µW/cm^2
Vibrations (1 m/s^2)	100 µW/cm^3

Table 4 provides a summary of the available power density for a given transduction technique that represents theoretical vs. practical obtainable values (Romero, 2010).

Table 4: Power Density Summary

Transduction Technique	Theoretical Value (mW/cm^3)	Practical Value (mW/cm^3)
Electromagnetic	400	4
Piezoelectric	343	19
Electrostatic	44	4

3. ENERGY HARVESTING FROM THE HUMAN BODY

Thermal energy generation from the human body is an appealing option since it requires no moving parts, but the efficiency of energy generation is limited to below 5% (Starner, 1996). The human body releases around 300 W of heat to the surroundings, if the entire body surface could be covered with such a generator, up to 20 W of power could be produced. Just covering 5% of the body leads to ~1 W. Smaller devices have proved useful for thermal generators in wristwatches, capable of producing 13-60 $\mu W/cm^2$ (Flipsen 2005; Paradiso and Starner, 2005). When adding and additional heat sink, the power generated can be as high as 400 $\mu W/cm^2$ (Mateu et al., 2007).

Harvesting energy from body activities promises an alternative to batteries for powering biomedical applications. Energy harvesters have the potential of extending the lifespan of battery-powered biomedical devices or even replace batteries as the sole energy source. Patient monitoring systems, drug delivery, neural implants, cardiac pacemakers, hearing aids, or even motorized prosthesis could be the recipients of this nascent technology.

In addition, the ever increasing use of wireless communications will add new challenges to battery powered devices. Wireless personal area networks and wireless body area networks are two of the new technologies aimed at medical monitoring for healthcare applications. Lower power consumption devices and larger batteries are currently the actual trend, but more applications constantly running and better interconnectivity are in direct contrast. An example of this can be found on the use of mobile technology. By the start of 21st century, cellphones charge could last up to one week without recharging, but were limited in additional functions. Today, best smartphones can hold a charge for the entire day with moderate use.

Medical applications have different power requirements depending on the required use. Powered prosthesis requires a higher consumption of several watts per day. Prosthesis with embedded electronics also needs to be charged often since power requirements are on the order of 1 W. Smaller devices usually require less power, such as the cardiac pacemakers and hearing aids. Since the former must operate uninterruptedly for several years, the battery occupies near half the available volume (Katz and Akiyama, 2007; Mallela et al., 2004). In the case of hearing aids, the button cell batteries need to be replaced periodically (Flipsen et al., 2004). Larger implantable devices, such as neurostimulators and infusion pumps, have a lifespan of 3-5 years because of the power consumption. Thus, biomedical applications range from mW to watts.

Inertial or kinetic generators harness energy using electromagnetic, electrostatic, or piezoelectric transduction. Electromagnetic generators use the relative motion of coils and magnets, in order to induce a voltage. Electrostatic devices require the change in capacitance (by varying the distance between the plates) or by a change in the dielectric properties (a moving dielectric) to generate an electrical charge. Piezoelectric generators take advantage of the piezoelectric properties, when such a material is subject to mechanical pressure; it produces a voltage in response. The larger the generator, the higher the power it can generate.

Generator can use several body activities, such as the heel strike, the up-and-down movement when walking, or the leg or arm swinging as well. For instance, a custom knee-brace electromagnetic generator that uses the leg swinging was capable of generating up to 4.8 W of power in a fashion similar to regenerative breaking (Li et al., 2008). Another electromagnetic transducer embedded in a backpack frame employed the up-and-down vertical movement of the payload to produce up to 7.4 W (Rome et al, 2005). Shoes with piezoelectric generators using the bending of the sole and/or the heel strike have shown power outputs ranging from 1 to 700 mW (Romero, et al., 2009). Knee implants with piezoelectric inserts have also shown to produce 850 µW of power continuously (Platt et al., 2005). The knee implants harness the vertical forces transmitted from the femur to the tibial tray, which can be as high as three times the body weight. Passive portable generators have also been developed. A tubular electromagnetic generator placed inside a backpack produced up to 0.95 mW while walking (Saha et al., 2008), while spherical designs provided up to 1.4mW when running (Bowers and Arnold, 2008) and planar geometries where capable of generating up to 0.5 mW (Romero et al., 2011).

Implantable piezoelectric generators (5x5 mm cross area, and 25-80 mm in lenght) that are activated by muscle contractions have also been presented. Muscles in the forearm, back of the trunk, and calf are estimated that could produce respectively 8µW, 54µW, and 690µW (Lewandowski et al., 2007). Running hamsters have also been tested for nanogenerators in a flexible substrate (Yang et al., 2009). Power densities up to 100-200 µW/cm2 have been show for this technology (Gao et al., 2007).

A summary of the generators developed and the power consumption of several devices is presented in Figure 1 (Romero, 2012a).

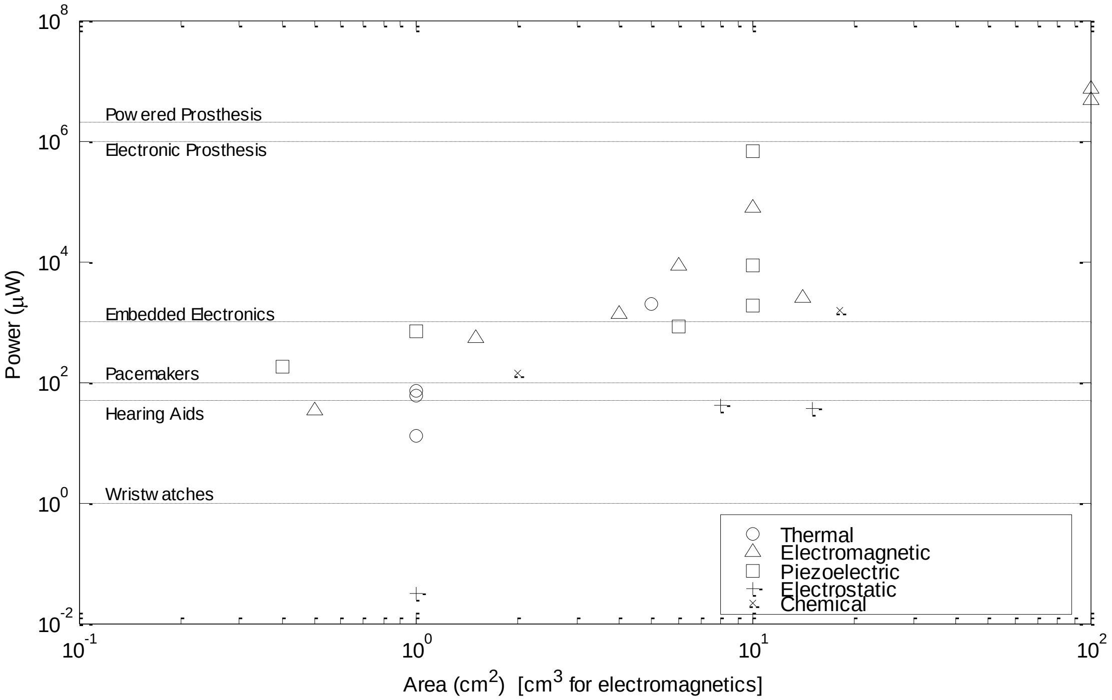

Figure 1: Energy Harvesters Summary for the Human Body (Romero, 2012a)

4. ENERGY HARVESTING FROM MACHINE VIBRATIONS

Energy generators using machine vibrations mainly use a cantilever beam structure, either piezoelectric or with an electromagnetic arrangement at the tip, to produce energy. Devices are typically designed to resonate at its natural frequency which is matched to the vibrating equipment frequency.

A PZT-5H piezoelectric material on top of a 0.1 mm thick AISI 316 steel when vibrating at 80 Hz produced 3 µW (Glynne-Jones et al., 2001). Another cantilever beam (17x7.7x3.6 mm), with a tungsten mass at the end, when oscillating at 120 Hz was capable of producing 375 µW (Roundy and Wright, 2004). A commercial device by Mide Technology Corp. has a device (3.6x1.7x0.39 in) that produces 500 µW when subject at 113 Hz and 1 g of acceleration (Mide, 2012). A composite piezoelectric aluminum plate (80x40x1 mm) was able to produce 2 mW when vibrating at its resonant frequency (Sodano et al., 2002). Radioactive sources have also been employed to excite vibration in a piezoelectric unimorph (Lal and Blanchard, 2004). An electromagnetic generator where NdFeB permanent magnets were placed at the end of a tip produced 1mW of power at 320 Hz of vibration (El-Hami et al., 2001). Another commercial device from Perpetuum Ltd. is capable of producing up to 5 mW of power with an acceleration of $0.1 m/s^2$ (Perpetuum, 2012).

5. ENERGY HARVESTING FROM MACHINE ROTATIONS

Axial-flux permanent magnet generators have been aimed at using the rotations of larger machinery or small devices, to produce energy for smaller applications. An extensive review of micro rotational devices has already been performed previously (Arnold, 2007). A summary of the most representative generators will be summarized.

An axial-flux permanent magnet generator using NdFeB with 7.5 mm in diameter ($0.5 cm^3$) produced 1mW of power at 30,000 rpm (Holmes et al., 2005). A larger device ($5.6 cm^3$) rotating at 100,000 rpm was capable of generating 16 W of power (Arnold, 2007). A commercial generator ($28 mm^3$) can produce 10 mW of power ($0.36 W/cm^3$) rotating at 5000 rpm (Kinetron, 2012). A permanent magnet rotor design using electroplated surface windings and soft magnetic material rotating at 305,000 rpm was capable of generating 8 W of power (Arnold et al., 2006). An axial-flux permanent magnet generator using a copper winding rather than lithography windings was developed as well. A single-phase prototype produced 0.41 mW at 2,200 rpm (Pan and Wu, 2007). A recent development using electroplated copper on flexible polyimide and NdFeB, produced 0.73 W at 29,500 rpm (Rivera-Nieves et al, 2011).

6. CONCLUSION

Energy harvesting is a new area that promises extended battery life or battery-less devices. This makes it possible for devices to have new applications. For instance, biomedical applications are one of the most interesting options since devices can be powered longer or new wireless applications can be born for patient monitoring. When matching actual energy harvesting technology and power consumption, new applications can be found.

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